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TECHNICAL REPORT

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A THEORETICAL DESCRIPTION OF THE PROCESS OF CHARGING AND
DISCHARGING A BORE EVACUATOR CHAMBER

BY

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A THEORETICAL DESCRIPTION OF THE PROCESS OF CHARGING
AND DISCHARGING A BORE EVACUATOR CHAMBER

ABSTRACT

The gas dynamics of a gun tube bore evacuator system or a gun gas operated chamber scavenger system may be theoretically described by ideal compressible flow relations. Differential equations and driving functions necessary to completely describe the operation of an evacuator system are developed based on the assumption of ideal adiabatic isentropic flow. A method of computer solution is proposed. Theoretical measures of scavenger effectiveness are presented.

Cross-Reference Data

Scavenger
Bore Evacuators
Gas Dynamics

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1. INTRODUCTION

The gas dynamics of a gun tube bore evacuator system or a gun gas operated chamber scavenger system may be theoretically described by ideal compressible flow relations. We need only assume that flow and mass storage are adiabatic isentropic and that no secondary combustion takes place in the storage chamber. From those assumptions the differential equations and driving functions necessary to completely describe the operation of an evacuator system follow directly.

This report presents a theoretical description of flow between chambers in Section two. Section three deals with the state of gases known to exist in gun tubes during the firing cycle. The rest of the report presents the application of these basics to the general bore evacuator problem, and includes a Section on theoretical measures of scavenger effectiveness.

2. THEORETICAL BACKGROUND

The four parts of this Section deal with sonic and subsonic flow from a reservoir, conditions in a reservoir while discharging, and conditions in a reservoir while it is being charged. All of this assumes isentropic flow of a perfect gas with no heat losses or gains.

A. A General Description of Sonic Flow from a Reservoir.

Assume that flow exists through an orifice from Chamber A to Chamber B.

P_a, P_b = Pressures in Chambers A and B

V_a, V_b = Volumes

T_a, T_b = Temperatures

m_a, m_b = Masses

ρ_a, ρ_b = Densities

γ = Ratio of Specific Heats

R = Gas Constant

A = Minimum Cross Sectional Area in the Opening between Chambers

γ = Average Velocity of the Gases as they Pass the Minimum Area

ρ = Density of the Gas at the Minimum Area

P = Pressure at Minimum Area

M = Mach Number at Minimum Area

For Flow from A to B:

$$P_a > P_b \quad (2.1)$$

Mass Flow is Given by:

$$-\dot{m}_a = \dot{m}_b = \rho \gamma A \quad (2.2)$$

Assuming Flow is Isentropic:

$$\frac{P_a}{P} = \left[1 + \frac{\gamma-1}{2} M^2 \right]^{\frac{\gamma}{\gamma-1}} \quad (2.3)$$

For Sonic Flow at Minimum Area:

$$P_b < P \quad (2.4)$$

and:

$$M = 1 \quad (2.5)$$

so that:

$$\frac{P_a}{P} = \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (2.6)$$

$$\frac{P_a}{P_b} > \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (2.7)$$

If condition (2.7) is satisfied the flow will be sonic.

Let:

a = Speed of Sound at Minimum Area

a_a = Speed of Sound in Chamber A

then:

$$\gamma = a \quad (2.8)$$

$$a_a = \sqrt{g_c \gamma R T_a} \quad (2.9)$$

with:

g_c = gravitational constant

also:

$$\frac{a_a}{a} = \left[1 + \frac{\gamma-1}{2} M^2 \right]^{1/2} \quad (2.10)$$

So that, substituting (2.5), (2.9), and (2.10) into (2.8):

$$\gamma = \sqrt{g_c \gamma R T_a \left(\frac{2}{\gamma+1} \right)} \quad (2.11)$$

For the density:

$$\frac{p_a}{p} = \left[1 + \frac{\gamma-1}{2} M^2 \right]^{\frac{1}{\gamma-1}} \quad (2.12)$$

$$p_a = \frac{P_a}{R T_a} \quad (2.13)$$

then:

$$\rho = \frac{P_a}{RT_a} \left[\frac{2}{\gamma+1} \right]^{\frac{1}{\gamma-1}} \quad (2.14)$$

and substituting (2.11) and (2.14) into (2.2):

$$-\dot{m}_a = A \sqrt{\frac{\gamma_c \gamma}{R}} \left[\frac{2}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \frac{P_a}{\sqrt{T_a}} \quad (2.15)$$

B. General Description of Subsonic Flow From A Reservoir.

Using the same notation as in Section A for sonic flow, subsonic flow exists from Chamber A to Chamber B if:

$$P_a > P_b \quad (2.16)$$

$$\frac{P_a}{P_b} < \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (2.17)$$

In this case:

$$M < 1 \quad (2.18)$$

So that:

$$\frac{P_a}{P_b} = \left[1 + \frac{\gamma-1}{2} M^2 \right]^{\frac{\gamma}{\gamma-1}} \quad (2.19)$$

$$\gamma = Ma \quad (2.20)$$

Equations (2.9), (2.10), (2.12), and (2.13) hold for this condition. Substituting these and (2.20) into the flow equation (2.2):

$$-\dot{m}_a = A \sqrt{\frac{2g_c \gamma}{R(\gamma-1)}} \frac{P_a}{\sqrt{T_a}} \frac{\left[\left(\frac{P_a}{P_b} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{1/2}}{\left(\frac{P_a}{P_b} \right)^{\frac{\gamma+1}{2\gamma}}} \quad (2.21)$$

C. Description of the State of Gases in a Finite Reservoir of Constant Volume While Reservoir is Discharging

Let:

t = Time

t_i = Time at Which Reservoir Conditions
Are Known

P_i = Initial Pressure

m_i = Initial Mass

V = Volume of Chamber

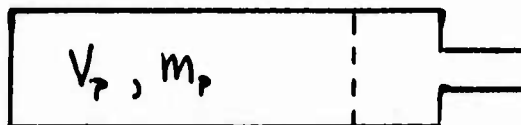


FIG 1

At $t = t_i$ introduce an imaginary divider in the chamber such that (FIG 1) a partial volume (V_p) and mass (m_p) are separated from the total. Then:

$$\frac{V_p}{V} = \frac{m_p}{m_i} \quad (2.22)$$

As mass leaves the chamber this fictitious divider moves to the right until at some time (t) the mass (m_p) occupies the entire volume. Assuming no heat transfer takes place, the original partial volume (V_p) has expanded adiabatically to the larger volume (V). Then:

$$\frac{V_p}{V} = \left(\frac{P}{P_i} \right)^{1/\gamma} \quad (2.23)$$

or, using Eqn (2.22) and noting that since the mass (m_p) occupies the entire volume the subscript (p) can be dropped:

$$\frac{m}{m_i} = \left(\frac{P}{P_i} \right)^{1/\gamma} \quad (2.24)$$

Equation (2.24) can be substituted into (2.15) (sonic flow) or (2.21) (subsonic flow) to solve for mass in the chamber as a function of time.

D. Sonic Exhaust from a Finite Reservoir of Constant Volume

As suggested in Section C, the appropriate equations are (2.15) and (2.24): (dropping the subscript a)

$$-\dot{m} = A \sqrt{\frac{g_c \gamma}{R}} \left[\frac{z}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \frac{P}{\sqrt{T}} \quad (2.25)$$

$$\frac{m}{m_i} = \left(\frac{P}{P_i} \right)^{1/\gamma} \quad (2.26)$$

Using the relationship:

$$PV = mRT \quad (2.27)$$

and substituting (2.26) into (2.25):

$$\dot{m} + A \sqrt{\frac{g_c \gamma P_i}{V m_i^\gamma}} \left[\frac{z}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} m^{\frac{\gamma+1}{2}} = 0 \quad (2.28)$$

equation (2.28) has initial condition:

$$m = m_i \quad (2.29)$$

at:

$$t = t_i$$

and solution:

$$m = m_i \left[1 + \frac{t - t_i}{\Theta} \right]^{-\frac{2}{\gamma-1}} \quad (2.30)$$

$$\Theta = \frac{2}{\gamma-1} \frac{1}{K} \left[\frac{m_i V}{g_c P_i A^2} \right]^{1/2} \quad (2.31)$$

$$K = \gamma^{1/2} \left[\frac{2}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \quad (2.32)$$

Substituting (2.30) into (2.26) and rearranging:

$$P = P_i \left[1 + \frac{t - t_i}{\Theta} \right]^{-\frac{2\gamma}{\gamma-1}} \quad (2.33)$$

from (2.27):

$$T = \frac{PV}{mR} \quad (2.34)$$

Substituting (2.30) and (2.33) into (2.34):

$$T = \frac{P_i V \left[1 + \frac{t-t_i}{\Theta} \right]^{-\frac{2\gamma}{\gamma-1}}}{m_i R \left[1 + \frac{t-t_i}{\Theta} \right]^{-\frac{2}{\gamma-1}}} \quad (2.35)$$

$$T = T_i \left[1 + \frac{t-t_i}{\Theta} \right]^{-2} \quad (2.36)$$

E. State of Gases in a Chamber During the Process of Charging the Chamber

Assuming flow is from Chamber A to Chamber B and is described by (2.15) or (2.21). Assume all conditions are known in both chambers at time (t_m). Then let:

$$t_{m+1} = t_m + \Delta t \quad (2.37)$$

$$m_{b,m+1} = m_{b,m} + \Delta m \quad (2.38)$$

or:

$$m_{b,m+1} = m_{b,m} + \dot{m}_b \Delta t \quad (2.39)$$

While this increment of Mass (Δm) was still in Chamber A (at $t = t_m$) it occupied an incremental volume (ΔV) given by:

$$\Delta V = \frac{(\Delta m) R T_{a,m}}{P_{a,m}} = \frac{\Delta m}{m_{a,m}} V_{a,m} \quad (2.40)$$

This incremental volume of gas expands adiabatically to some partial volume (V_{Δ}) in Chamber B and to a pressure (P_{Δ}) in Chamber B after the expansion such that:

$$\frac{P_{\Delta}}{P_{a,m}} = \left(\frac{\Delta V}{V_{\Delta}} \right)^{\gamma} \quad (2.41)$$

At the same time, the gases already in Chamber B are being compressed adiabatically to pressure (P_{Δ}) and a partial volume ($V_{i-\Delta}$) such that:

$$V_b = V_{\Delta} + V_{i-\Delta} \quad (2.42)$$

and:

$$\frac{P_{\Delta}}{P_{b,m}} = \left(\frac{V_b}{V_{i-\Delta}} \right)^{\gamma} \quad (2.43)$$

solving equations (2.40) through (2.43) simultaneously:

$$P_{\Delta} = P_{b,m} \left[1 + \frac{\dot{m}_b \Delta t V_{a,m}}{m_{a,m} V_b} \left(\frac{P_{a,m}}{P_{b,m}} \right)^{1/\gamma} \right]^{\gamma} \quad (2.44)$$

The incremental mass (Δm) is now at a temperature (T_{Δ}) given by:

$$T_{\Delta} = \frac{P_{\Delta} V_{\Delta}}{\Delta m R} \quad (2.45)$$

and the compressed mass ($M_{b,m}$) is now at a temperature ($T_{1-\Delta}$) given by:

$$T_{1-\Delta} = \frac{P_{\Delta} V_{1-\Delta}}{M_{b,m} R} \quad (2.46)$$

The mixing is assumed to be a heat transfer process such that the final temperature ($T_{b,m+1}$) is given by:

$$T_{b,m+1} = \frac{\Delta M T_{\Delta} + M_{b,m} T_{1-\Delta}}{M_{b,m+1}} \quad (2.47)$$

Let:

$V_{f\Delta}$ = Final Volume of ΔM

$V_{f,1-\Delta}$ = Final Volume of $M_{b,m}$

Then:

$$V_{f\Delta} = \frac{\Delta M R T_{b,m+1}}{P_{b,m+1}} \quad (2.48)$$

$$V_{f,1-\Delta} = \frac{M_{b,m} R T_{b,m+1}}{P_{b,m+1}} \quad (2.49)$$

$$V_{f\Delta} + V_{f,1-\Delta} = V_b \quad (2.50)$$

Solving (2.45) through (2.50):

$$P_{b,m+1} = P_a \quad (2.51)$$

$$P_{b,m+1} = P_{b,m} \left[1 + \frac{\dot{m} \Delta t V_{a,m}}{m_{a,m} V_b} \left(\frac{P_{a,m}}{P_{b,m}} \right)^{1/\gamma} \right]^\gamma \quad (2.52)$$

Equation (2.52) could be rewritten:

$$P_b + \dot{P}_b \Delta t = P_b \left[1 + \frac{V_a}{m_a V_b} \left(\frac{P_a}{P_b} \right)^{1/\gamma} \dot{m} \Delta t \right]^\gamma \quad (2.53)$$

or:

$$P_b + \dot{P}_b \Delta t = P_b \left[1 + C \dot{m} \Delta t \right]^\gamma \quad (2.54)$$

For small enough Δt :

$$\left[1 + C \dot{m} \Delta t \right]^\gamma = 1 + \gamma C \dot{m} \Delta t \quad (2.55)$$

$$P_b + \dot{P}_b \Delta t = P_b + P_b \gamma C \dot{m} \Delta t \quad (2.56)$$

$$\dot{P}_b = \frac{P_b \gamma}{V_b} \frac{V_a}{m_a} \left(\frac{P_a}{P_b} \right)^{1/\gamma} \dot{m} \quad (2.57)$$

or:

$$\dot{P}_b = \frac{P_b \gamma}{V_b} \frac{RT_a}{P_a} \left(\frac{P_a}{P_b} \right)^{1/\gamma} \dot{m} \quad (2.58)$$

3. STATE OF GASES IN THE GUN TUBE

It is sufficient to describe the pressure and temperature of the gases in the tube.

Chamber Area

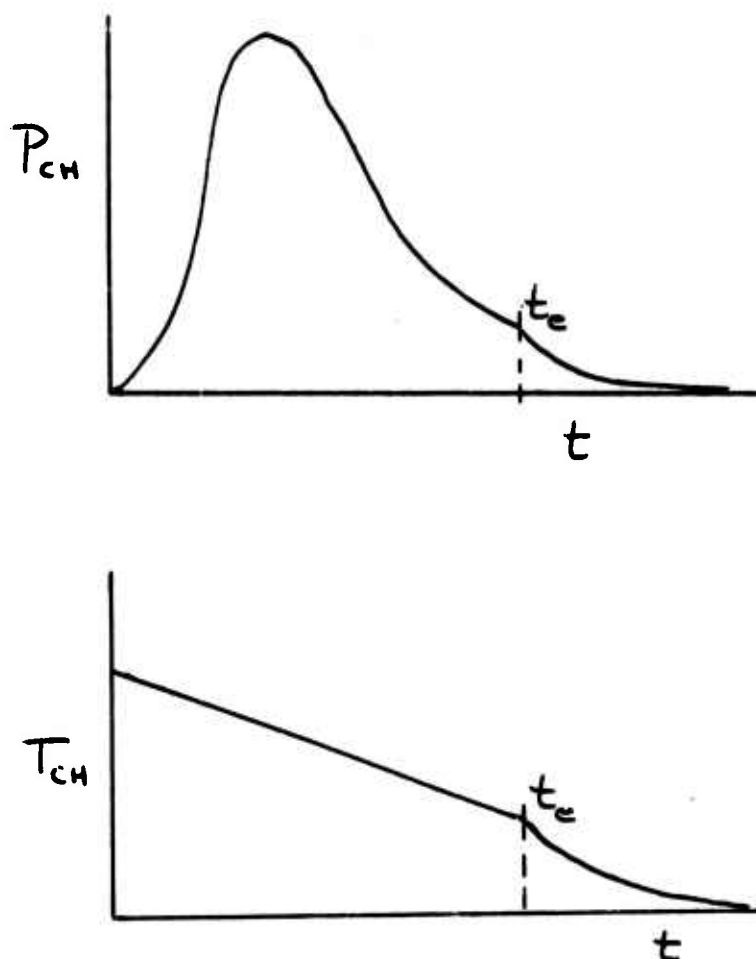


FIG. II

Let:

P_{CH} = Chamber Pressure

T_{CH} = Chamber Temperature

t_e = Time at Projectile Exit

(a) for: $0 < t < t_e$

P_{CH} = Tabulated Function of Time

T_{CH} = Tabulated Function of Time

If information on temperatures is not available, T_{CH} can be reasonably approximated for most ammunition by:

$$T_{CH} = 4700 - 2000 t/t_e \quad (3.1)$$

(b) for:

After exit, assume that the tube gases satisfy the requirements of Section 2-D, that is: sonic exhaust from a finite reservoir of constant volume. Then:

$$P_{CH} = P_e \left[1 + \frac{t - t_e}{\Theta_{CH}} \right]^n \quad (3.2)$$

with:

P_e = Pressure at Projectile Exit

$$n = - \frac{2\gamma}{\gamma - 1} \quad (3.3)$$

$$\Theta_{CH} = \frac{2}{\gamma - 1} \frac{1}{K} \left[\frac{m_e V_t}{g_c P_e A_B^2} \right]^{1/2} \quad (3.4)$$

$$K = \gamma^{1/2} \left[\frac{2}{\gamma + 1} \right]^{\frac{\gamma + 1}{2(\gamma - 1)}} \quad (3.5)$$

m_e = Mass of Propellant

V_t = Internal Volume of Tube and Chamber

A_B = Area of Bore

And:

$$T_{CH} = T_e \left[1 + \frac{t - t_e}{\Theta_{CH}} \right]^{-2} \quad (3.6)$$

Down Bore

The above pressure and temperature curves are reasonably accurate at all points in the tube until projectile exit. At points downbore from the origin of rifling, the above can be modified after projectile exit to account for flow of gas toward the muzzle. Let:

V_M = Muzzle Velocity of Gas (Sonic)

V_D = Velocity of Gas at a Point in the Tube

$$V_D = \frac{d}{L} V_M \quad (3.7)$$

with

d = Distance Downbore from the Origin of Rifling

L = Distance from Origin of Rifling to Muzzle

Since the gases are moving at sonic velocity at the muzzle:

$$V_M = \sqrt{g_c \gamma R T_M} \quad (3.8)$$

T_M = Temperature at the Muzzle

But:

$$\frac{T_{CH}}{T_M} = 1 + \frac{\gamma-1}{2} M^2 \quad (3.9)$$

At Throat:

$$M = 1 \quad (3.10)$$

$$T_M = \frac{2 T_{CH}}{\gamma + 1} \quad (3.11)$$

$$V_M = \sqrt{\frac{2 g_c \gamma R T_{CH}}{\gamma + 1}} \quad (3.12)$$

To estimate the Mach No. at the position d:

$$\frac{a_{CH}}{a_D} = \left[1 + \frac{\gamma-1}{2} M_D^2 \right]^{1/2} \quad (3.13)$$

$$M_D = \frac{V_D}{a_D} \quad (3.14)$$

With:

a_d = Sonic Velocity at Position d

a_{ch} = Sonic Velocity in Chamber

Eliminating a_d from (3.13) and (3.14):

$$M_d^2 = \frac{V_d^2}{a_{ch}^2 - \frac{\gamma-1}{2} V_d^2} \quad (3.15)$$

with:

$$a_{ch} = \sqrt{g_c \gamma R T_{ch}} \quad (3.16)$$

substituting (3.7), (3.12), and (3.16) into (3.15):

$$M_d^2 = \frac{2 d^2}{(\gamma+1) l^2 - (\gamma-1) d^2} \quad (3.17)$$

Then from the flow equations, the conditions at position d are given by:

$$T_d = \frac{T_{ch}}{1 + \frac{\gamma-1}{2} M_d^2} \quad (3.18)$$

$$P_d = \frac{P_{ch}}{\left[1 + \frac{\gamma-1}{2} M_d^2\right]^{\frac{\gamma}{\gamma-1}}} \quad (3.19)$$

To summarize: After projectile exit, equations (3.2) and (3.6) describe conditions in the chamber, and equations (3.17), (3.18) and (3.19) correct for flow out the muzzle for points downbore.

4. APPLICATION TO A BORE EVACUATOR

It is first assumed that tube conditions are unaffected by the evacuator can and that those conditions are described by the equations in Section F.

m_{CN} = Mass in Evacuator

P_{CN} = Pressure in Evacuator

T_{CN} = Temperature in Evacuator

V_{CN} = Volume of Evacuator

A = Effective Area Open to Flow

Note that A depends on which holes have been uncovered at any instant in time and upon flow direction if one-way valves restrict flow. It is assumed that all one-way valves work perfectly: that is, no restriction to flow in one direction, total restriction in the other.

a. Subsonic charging of evacuator exists if (Equations (2.16) and (2.17)):

$$1 < \frac{P_{CH}}{P_{CN}} < \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (4.1)$$

Then from (2.21) and (2.58):

$$\dot{m}_{CN} = A \sqrt{\frac{2g_c\gamma}{R(\gamma-1)}} \frac{P_{CH}}{\sqrt{T_{CH}}} \frac{\left[\left(\frac{P_{CH}}{P_{CN}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{\frac{1}{2}}}{\left(\frac{P_{CH}}{P_{CN}} \right)^{\frac{\gamma+1}{2\gamma}}} \quad (4.2)$$

$$\dot{P}_{CN} = \frac{P_{CN} \gamma}{V_{CN}} \frac{RT_{CH}}{P_{CH}} \left(\frac{P_{CH}}{P_{CN}} \right)^{1/\gamma} \dot{m}_{CN} \quad (4.3)$$

b. Sonic charging of evacuator exists if (Equation (2.7)):

$$\frac{P_{CH}}{P_{CN}} > \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (4.4)$$

Then from Equations (2.15) and (2.58):

$$\dot{m}_{CN} = A \sqrt{\frac{g_c \gamma}{R}} \left[\frac{2}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \frac{P_{CN}}{\sqrt{T_{CN}}} \quad (4.5)$$

$$\dot{P}_{CN} = \frac{P_{CN} \gamma}{V_{CN}} \frac{RT_{CH}}{P_{CH}} \left(\frac{P_{CH}}{P_{CN}} \right)^{1/\gamma} \dot{m}_{CN} \quad (4.6)$$

c. Subsonic discharge exists if (Equations (2.16) and (2.17)):

$$1 < \frac{P_{CN}}{P_{CH}} < \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (4.7)$$

Then from (2.21):

$$\dot{m}_{CN} = -A \sqrt{\frac{2g_c \gamma}{R(\gamma-1)}} \frac{P_{CN}}{\sqrt{T_{CN}}} \frac{\left[\left(\frac{P_{CN}}{P_{CH}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{\frac{1}{2}}}{\left(\frac{P_{CN}}{P_{CH}} \right)^{\frac{\gamma+1}{2\gamma}}} \quad (4.8)$$

and:

$$\dot{P}_{CN} = \frac{P_{CN} \gamma}{M_{CN}} \dot{m}_{CN} \quad (4.9)$$

Where equation (4.9) comes from differentiation of (2.24).

d. Sonic discharge exists if (Equation (2.7)):

$$\frac{P_{CN}}{P_{CH}} > \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (4.10)$$

Then from Section 2-D:

$$P_{CN} = P_{cne} \left[1 + \frac{t - t_{cne}}{\Theta_{CN}} \right]^{-\frac{2\gamma}{\gamma-1}} \quad (4.11)$$

$$M_{CN} = M_{cne} \left[1 + \frac{t - t_{cne}}{\Theta_{CN}} \right]^{-\frac{2}{\gamma-1}} \quad (4.12)$$

With:

t_{CNe} = Time Sonic Discharge Begins

P_{CNe} = Evacuator Pressure @ t_{CNe}

M_{CNe} = Mass in Evacuator @ t_{CNe}

$$\Theta_{CN} = \frac{2}{\gamma-1} \frac{1}{K} \left[\frac{M_{CNe} V_{CN}}{g_c P_{CNe} A^2} \right]^{1/2} \quad (4.13)$$

$$K = \gamma^{1/2} \left[\frac{2}{\gamma+1} \right]^{\frac{\gamma+1}{2(\gamma-1)}} \quad (4.14)$$

At any instant in time, the ratio of tube and evacuator pressures can be checked against conditions (4.1), (4.4), (4.7), and (4.10) to determine which type of flow exists. For charging or subsonic discharging, the appropriate differential equations are of the form:

$$\dot{M}_{CN} = f(P_{CH}, P_{CN}, T_{CH}, T_{CN}) \quad (4.15)$$

$$\dot{P}_{CN} = g(P_{CH}, P_{CN}, T_{CH}, T_{CN}, \dot{M}_{CN}, M_{CN}) \quad (4.16)$$

In these equations, P_{CH} and T_{CH} are known functions of time and one variable can be eliminated with:

$$T_{CN} = \frac{P_{CN} V_{CN}}{M_{CN} R} \quad (4.17)$$

Initial conditions for the above equations are:

$$\left. \begin{aligned} P_{CN} &= 15 \text{ PSI} \\ T_{CN} &= 540^\circ \text{ RANKIN} \\ M_{CN} &= P_{CN} V_{CN} / R T_{CN} \end{aligned} \right\} @t=0 \quad (4.18)$$

These two simultaneous differential equations, (4.15) and (4.16), can be solved with any number of numerical techniques. A computer program developed for this analysis could utilize a fourth-order Runge-Kutta solution, for instance.

When the sonic discharge begins, equations (4.11) and (4.12) describe conditions exactly until the evacuator is nearly empty.

5. A THEORETICAL MEASURE OF THE EFFECTIVENESS OF DIFFERENT BORE EVACUATOR DESIGNS

Several methods of system evaluation have been considered. It is difficult without some experimental analysis to pin down a definite criteria. The methods presently under consideration are as follows:

1. Duration of exhaust jet
2. Duration of sonic exhaust jet
3. Exhaust jet thrust
4. Exhaust jet impulse
5. Equivalent volume of gas at STP

Obviously these measures give no indication as to the structural integrity of a given configuration, and the importance of each to scouring or scavenging is largely a matter of opinion. At present, however, these are the best available.

1. Duration of exhaust jet.

The differential equations which describe the exhaust are such that evacuator pressure approaches atmospheric pressure asymptotically. Theoretically, then, the exhaust jet lasts indefinitely. For practical purposes, however, the exhaust is effectively finished when evacuator pressure is one or two psi above atmospheric.

2. Duration of sonic exhaust jet.

Sonic duration can be calculated directly when

the sonic flow beings. Equation (4.11):

$$P_{CN} = P_{CNE} \left[1 + \frac{t - t_{CNE}}{\Theta_{CN}} \right]^{-\frac{2\gamma}{\gamma-1}} \quad (5.1)$$

Sonic flow ceases when:

$$\frac{P_{CN}}{15} = \left[\frac{1+\gamma}{2} \right]^{\frac{\gamma}{\gamma-1}} \quad (5.2)$$

Substituting (5.2) into (5.1) and solving for the time interval:

$$\begin{aligned} t_{SJ} &= t - t_{CNE} \\ &= \Theta_{CN} \left[\left(\frac{15}{P_{CNE}} \right)^{\frac{1-\gamma}{2\gamma}} \sqrt{\frac{2}{1+\gamma}} - 1 \right] \quad (5.3) \end{aligned}$$

3. Exhaust Jet Thrust

Thrust has been proposed as a measure of the force available in the jet for scouring purposes.

Thrust (T_h) is given by:

$$T_h = \dot{m} V \quad (5.4)$$

with:

$$\dot{m} = \rho \gamma A \quad (5.5)$$

then:

$$T_h = \frac{(\dot{m})^2}{\rho A} \quad (5.6)$$

(a) Subsonic flow:

$$\rho = \rho_{CN} \left(\frac{P_{CH}}{P_{CN}} \right)^{1/\gamma} \quad (5.7)$$

$$\rho_{CN} = \frac{M_{CN}}{V_{CN}} \quad (5.8)$$

Substituting (5.7) and (5.8) into (5.6)

$$T_h = \frac{(\dot{m})^2 V_{CN}}{A M_{CN}} \left(\frac{P_{CH}}{P_{CN}} \right)^{1/\gamma} \quad (5.9)$$

The Runge-Kutta solution of the differential equations necessitates calculation of \dot{m} and m_{CN} for each instant of time, so that (5.9) need not be modified further for subsonic flow.

(b) Sonic flow:

From equation (4.12):

$$M_{CN} = M_{cNe} \left[1 + \frac{t - t_{cNe}}{\Theta_{CN}} \right]^{-\frac{2}{\gamma-1}} \quad (5.10)$$

Differentiating:

$$\dot{M} = -\dot{M}_{CN} = \frac{2}{\gamma-1} \frac{M_{cNe}}{\Theta_{CN}} \left[1 + \frac{t - t_{cNe}}{\Theta_{CN}} \right]^{\frac{1+\gamma}{1-\gamma}} \quad (5.11)$$

From Equation (2.14)

$$P = \frac{P_{CN}}{R T_{CN}} \left[\frac{2}{\gamma+1} \right]^{\frac{1}{\gamma-1}} \quad (5.12)$$

or;

$$P = \frac{M_{CN}}{V_{CN}} \left[\frac{2}{\gamma+1} \right]^{\frac{1}{\gamma-1}} \quad (5.13)$$

Substituting (5.10), (5.11) and (5.13) into (5.6)

$$T_h = \frac{4 M_{cNe} V_{CN}}{A \Theta_{CN}^2 (\gamma-1)^2} \left[\frac{\gamma+1}{2} \right]^{\frac{1}{\gamma-1}} \left[1 + \frac{t - t_{cNe}}{\Theta_{CN}} \right]^{-\frac{2\gamma}{\gamma-1}} \quad (5.14)$$

Peak thrust at $t = t_{cNe}$:

$$T_h = \frac{4 M_{cne} V_{cn}}{A \Theta_{cn}^2 (\gamma-1)^2} \left[\frac{\gamma+1}{2} \right]^{\frac{1}{\gamma-1}} \quad (5.15)$$

4. Exhaust Jet Impulse.

Thrust integrated over time is impulse. The impulse is indicative of the total momentum available in the jet.

$$I = \int T_h dt \quad (5.16)$$

a. Subsonic flow:

During subsonic exhaust the thrust is calculated for each time interval. The integral can be a simple trapezoidal-rule summation.

b. Sonic flow:

$$I = I_o + \int_{t_{cne}}^t T_h dt \quad (5.17)$$

with:

I_o = Impulse for first subsonic exhaust

let:

$$I_{son} = \int_{t_{cne}}^t T_h dt \quad (5.18)$$

Substituting (5.14) and (5.18) and integrating:

$$I_{scn} = \frac{4 M_{cne} V_{cn}}{A \Theta_{cn} (\gamma^2 - 1)} \left[\frac{\gamma + 1}{2} \right]^{\frac{1}{\gamma - 1}} \left[1 - \left(1 + \frac{t - t_{cne}}{\Theta_{cn}} \right)^{\frac{1 + \gamma}{1 - \gamma}} \right] \quad (5.19)$$

Equation (5.19) holds for:

$$t_{cne} < t < t_{cne} + t_{st} \quad (5.20)$$

5. Equivalent volume of gas at STP:

When evacuator is fully charged let:

M_{cnf} = Total mass in evacuator

P_{cnf} = Peak Evacuator pressure

Then:

$$T_{cnf} = P_{cnf} V_{cn} / M_{cnf} R \quad (5.21)$$

$$V_{STP} = V_{cn} \left(\frac{540}{T_{cnf}} \right) \left(\frac{P_{cnf}}{15} \right) \quad (5.22)$$

or, substituting (5.21) into (5.22)

$$V_{STP} = 36 M_{cnf} R \quad (5.23)$$

6. GENERAL DISCUSSION

The bore evacuator analysis presented above is somewhat lacking in several respects:

1. Heat would be transferred from the gas to the container walls. This would cool the gas, thus reducing its pressure and ultimately its effectiveness. It was assumed in the above analysis that heat transfer was negligible since the time duration was short. Considering the temperatures attained in gun tubes firing, where gases are contained for an even shorter time, the above assumption is at best approximate.

2. No valving system is perfect. Valves which take time to close, impose flow restrictions, leak when supposedly closed, etc., would tend to reduce the bore evacuator effectiveness.

3. The thrust for most bore evacuator configurations would appear as in curve one of Figure III below.

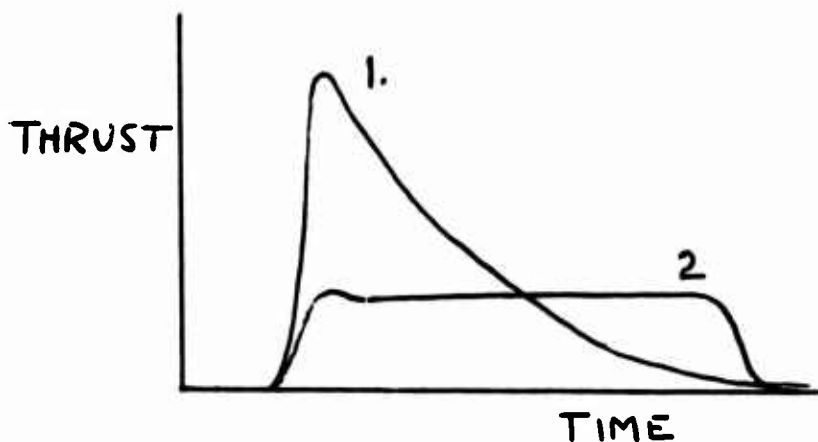


FIG III

Curve two of Figure III indicates the type thrust function available from an externally powered scavenger system. The area under each curve is the impulse. A bore evacuator delivering the same impulse as an externally powered scavenger would have a much higher peak thrust. However, over a considerable time period the bore evacuator delivers a much lower thrust. At present no rationale has been developed which could be used to predict what these differences in the thrust function mean in terms of purging or scouring effectiveness. The higher peak thrust could break loose adhered residue more effectively. However, the jet has in general a shorter time to be effective.

4. It was assumed that the amount of mass entering the evacuator was small enough that it would have a negligible effect on the interior ballistics of the gun. This is reasonably true if only gas flow is considered. However, no estimate could be made as to how much unburnt propellant might be blown into the evacuator before burning is complete. Such an occurrence would completely invalidate this analysis since the interior ballistics would be seriously affected. If the propellant were to burn while in the evacuator, the pressures would rise much higher than the theoretical values calculated. Any evacuator near the chamber end of the gun would have to be

designed as a high-pressure container as insurance against this contingency.

5. Discharge coefficients were assumed to be unity. Although charging and discharging holes might be designed so that this would be approximately valid, in all probability some flow losses would occur.

In addition to the above problems with the analysis, there exist problems with any bore evacuator for which a completely separate analysis is necessary.

1. This type of system will never completely clear the tube of smoke and noxious gases. Since gun gas is being used for purging, the tube will still contain products of combustion after the evacuator is exhausted. Some secondary purging system must be used to clear the tube of smoke.

2. Any gun-gas operated scavenger necessitates drilling holes in the tube or chamber, introducing a valving system, providing a storage container. All such items pose structural reliability problems, sealing problems, etc.

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